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EVALUATION OF A HYBRID-PISTON PULSED DETONATION ENGINE

Brian Frankey, Fred Schauer, Royce Bradley*, and John Hoke*
Air Force Research Laboratory, Propulsion Directorate
Wright-Patterson AFB, OH 45433
*Innovative Scientific Solutions, Inc.
Dayton, OH 45440

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Abstract

Experiments are conducted on a hybrid piston-pulsed detonation engine to evaluate the power extraction and system interaction issues. The hybrid engine is constructed using a four-cylinder motorcycle engine with a spacer block between the valves and pistons. Four detonation tubes, one for each cylinder, are placed perpendicular to the direction of the piston travel. A deflagration to detonation transition (DDT) is used to achieve detonations. The piston is in the deflagration region of the DDT. This hybrid engine has a critical starting frequency. Above this frequency the engine will self-actuate and produce excess power. Below this frequency, the power produced is less than that required to self-actuate and the engine decelerates after the starter motor is disengaged. The hybrid piston-pulsed-detonation-engine constructed for these experiments is capable of producing 20 hp and 50 lbf of thrust simultaneously.

Introduction

Over the past ten years, a resurgence of interest and research directed toward pulsed detonation engines (PDE's) has occurred[1]. Recent advances in computers and diagnostic tools have allowed researchers to overcome many of the technology hurdles hindering the construction of a practical PDE. Depending on the application, these obstacles include detonation initiation, valving, or flow control, aspiration, power extraction and others. Traditionally, the PDE has been viewed as a thrust-producing engine; however, for the PDE to work in an application like a commercial passenger jet, a second engine or power extraction from the PDE would be required to run sub-systems such as lights and air conditioning.

* Author to whom correspondence should be addressed: frederick.schauer@wpafb.af.mil, (937) 255-6462 Fax: (937) 656-4570

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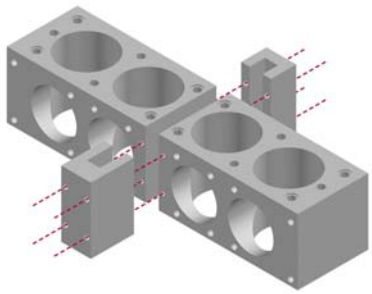
In this paper, a concept for extracting shaft-power from a pulsed detonation engine is described and the results of experiments conducted on the device are presented and analyzed.

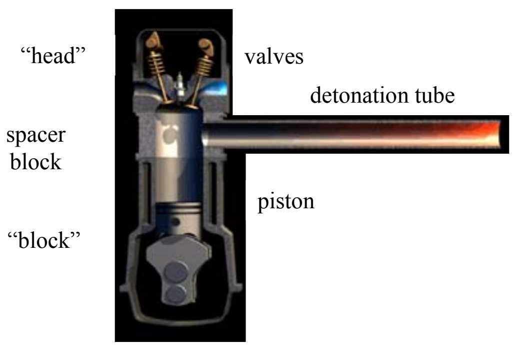
Experimental Apparatus and Procedure

A hybrid piston-pulsed-detonation-engine (hybrid piston-PDE) was constructed by modifying a stock four-cylinder four-stroke motorcycle engine. A spacer block was placed between the "head" and "block" of the motorcycle to allow for the creation of four airflow passages for the four detonation tubes. The spacer block allowed one detonation tube, one for each cylinder, to be placed perpendicular to the travel of the piston. The 3-D CAD drawing of the spacer block is shown in Fig. 1a and a drawing of a cross section of the engine with the spacer block and detonation tube is given in Fig. 1b.

With the spacer block installed, the cam-chain and the oil supply and return lines to the "head" had to be extended. A picture of the assembled hybrid piston-PDE is shown in Fig 2. The spark and valve timing were altered from that of the stock engine. To maximize the power output of the hybrid engine the spark timing was adjusted so that the pressure from the detonation cycle occurred while the piston was traveling downward at its maximum velocity. The valve and spark timing relative to the piston position is depicted in Fig. 3.



(a)



(b)

Figure 1. Spacer bock: a) 3D cad drawing and b) Drawing of a cross section of the assembled hybrid piston-PDE

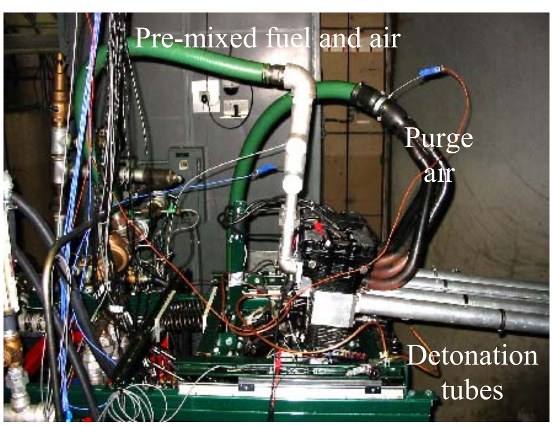


Figure 2. Picture of the hybrid piston-PDE

Starting at the top of the diagram in Fig. 3 and moving clockwise, the intake valve closed approximately 15 cam-degrees after the piston had reached top dead center (TDC). A stoichiometric mixture of hydrogen and air flowed through the intake valve when it was open. At approximately 30 cam-degrees, the spark plug was fired. The stock ignition system was used to initiate deflagration of the fuel air mixture. The timing of the spark was altered by adjusting the circumferential position of the Hall effect sensor around the crankshaft. A Shelkin shocking spiral was used to transition the deflagration to a detonation. For several milliseconds after the detonation wave exited the detonation tube, the pressure on the piston of the motorcycle was above atmospheric pressure. The spark timing was chosen to maximize the PdV work extracted by the piston.

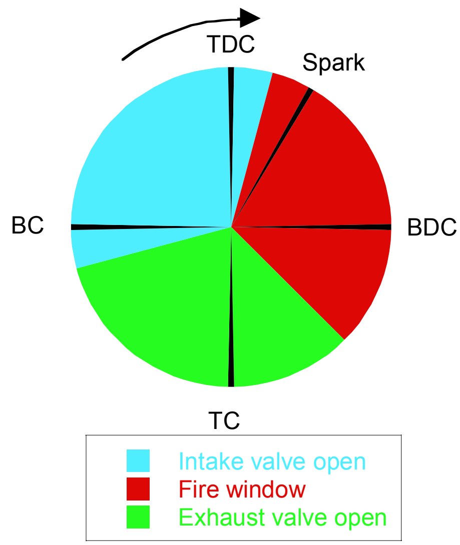


Figure 3. Valve and spark timing relative to piston position, note that the crankshaft makes two revolutions for every one that the camshaft makes. (TDC is top dead center, BDC is bottom dead center, TC is top center and BC is bottom center)

By the time the piston reached bottom dead center (BDC), the pressure on the piston had reached atmospheric pressure and the remainder of the possible “fire window” was not used. At approximately 135 cam degrees, the exhaust valve opened and purge air flowed into the cylinder and down the detonation tube to separate the hot exhaust products from the next air-fuel charge. Note that the motorcycle engine was a four-stroke, so the piston traveled up and down twice for each cycle of the camshaft. Since the exhaust products were not pushed out of the cylinder by the piston, a two-stroke engine may have been better suited for this experiment. The intake valve opened at approximately 255 cam degrees after TDC and a pre-mixed charge of air and fuel filled the combustion chamber of the motorcycle and the detonation tube, repeating the cycle. Facility air compressors and controls were used to supply and regulate air and fuel flow to the hybrid piston-PDE. A good description of the facility is given by Schauer *et al*.[2]

A piston engine is often referred to as an air pump since the motion of the piston in concert with the valve train can be used to draw in fresh air and expel exhaust products. However in the hybrid piston-PDE, the piston cannot be used to pump air since the detonation tube and hence the cylinder was always open to the atmosphere, refer to Fig 1b.

As with almost any internal combustion engine, external power is supplied to "start" the engine. In this experiment, power to start the engine was supplied by a 20 hp variable speed electric motor. A chain was used to connect the electric motor to the output sprocket of the transmission. With the transmission in gear and the clutch engaged, power from the electric motor was transmitted to the crankshaft and from the crankshaft to the camshaft via the timing chain.

With the engine motored by the starter motor, the air and fuel flow rates were adjusted to match the detonation tube volume and engine frequency. A spark from the stock ignition system was used to ignite the fuel air mixture. Once the engine completed several cycles, the clutch was remotely disengaged—separating the "starting" electric motor from the hybrid piston-PDE. If the power extracted by the pistons was equal to the power required to rotate the crankshaft, camshaft and overcome the system friction, the rotational frequency of the hybrid piston-PDE would remain constant after the electric "starter" motor was disengaged. If excess power were produced, the rotational speed of the hybrid piston-PDE would increase. Conversely, the rotational speed of the hybrid piston-PDE would decelerate and quickly stop if the power produced was lower than the required power. As will be discussed in the "Analysis" section, a critical-starting-rotational speed must be obtained for this engine to produce enough power to self-actuate and continue to operate after the starter motor was disengaged.

Experimental Results

Experiments were conducted to determine if the hybrid piston-PDE would operate as anticipated and to determine the power and thrust produced by the engine. In Fig. 4, the instantaneous pressure at the head of the detonation tube is plotted verses time. From zero to three seconds, the fuel flow was gradually increased until the equivalence ratio was unity. The magnitude of the head pressure during this start-up time generally increased, see Fig. 4. At approximately 5.5 seconds, the clutch was disengaged separating the hybrid-piston PDE from the electric "starting" motor. In this particular configuration, the engine accelerated and the time between consecutive pressure spikes in Fig 4, decreased. From Fig, 4, it is evident from the magnitude of the pressure spikes that the fuel and air supply systems were being adjusted during the experiment to match the accelerating engine.

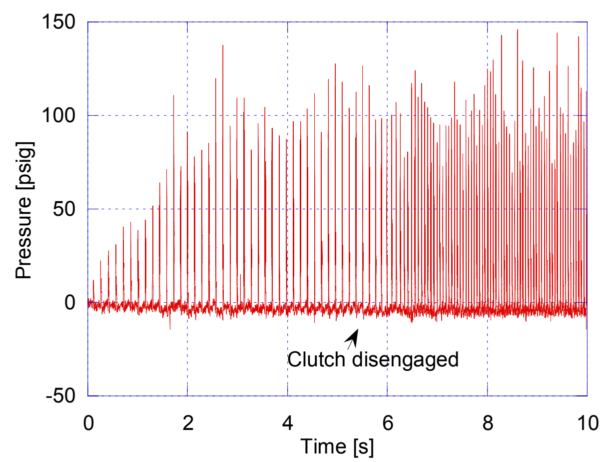


Figure 4. Instantaneous head pressure verses time: accelerating hybrid-piston-PDE

In Fig 5, the detonation frequency of a single tube is plotted versus time. In this experiment, the starting frequency was above the critical starting frequency. At approximately 3.5 seconds, the clutch was disengaged and the hybrid piston-PDE accelerated from a single tube detonation frequency of approximately 11 Hz to 21 Hz.

At 11 Hz, excess power was being produced which caused the rotational speed of the engine to accelerate. At 21 Hz, the hybrid engine reached a new equilibrium where the power required to actuate the

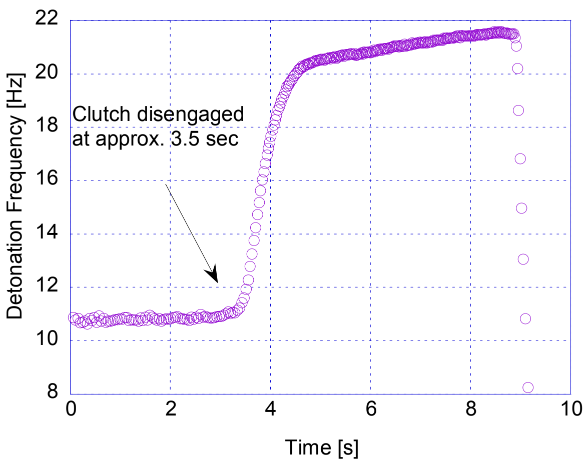
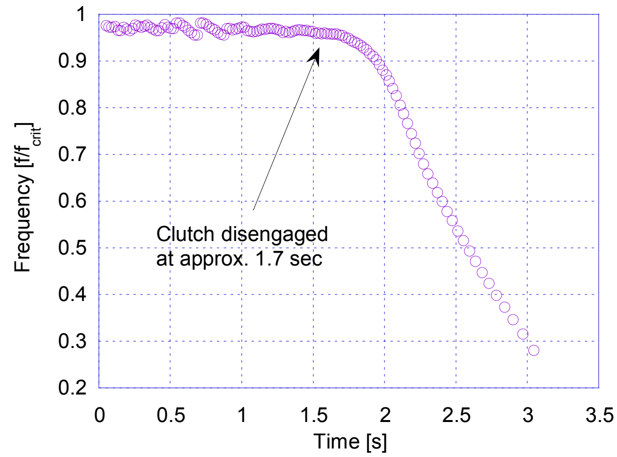
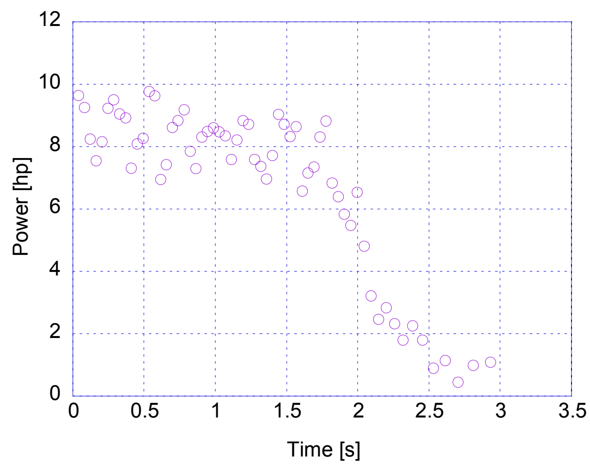


Figure 5. Detonation tube frequency verses time



(a)



(b)

Figure 6. Below the critical starting frequency the hybrid piston-PDE failed to self-actuate, (a) normalized frequency verses time and (b) calculated power output during this experiment

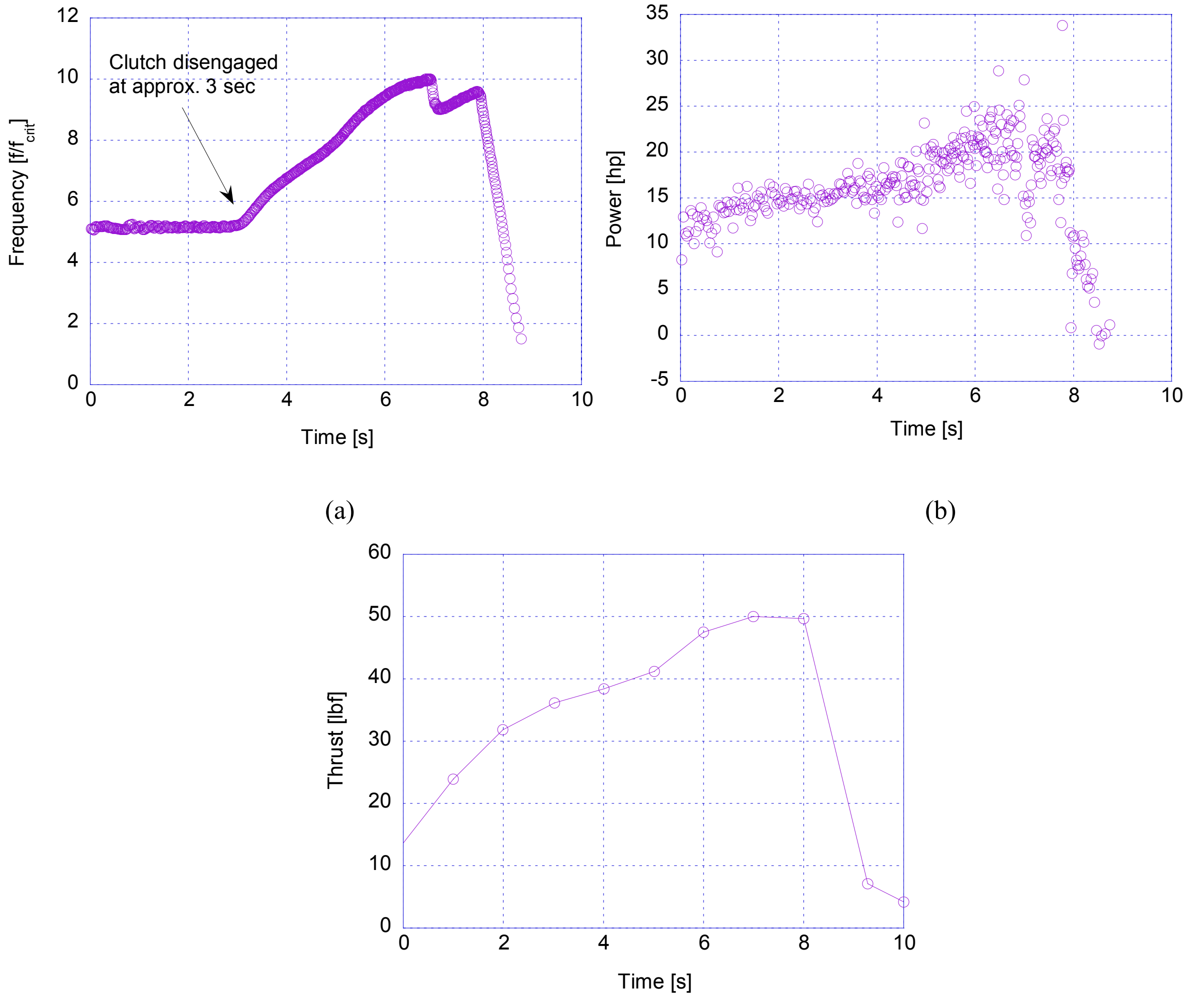
engine was equal to the power produced by the engine. The air and fuel flow were set for operation at 11 Hz; therefore, at 21 Hz, the air and fuel flow were approximately half that required to completely fill the detonation tube prior to detonating. The control system for the air and fuel could not maintain ideal conditions with the rapid change in operating frequency of the hybrid engine. The experiment was automatically terminated at 9 seconds because the temperature of the detonation tubes exceeded a preset limit. In this experiment, the detonation tube consisted of a 72" long 2" diameter tube with a 1.84 to 1 bell reducer used as a converging nozzle.

At a starting frequency below the critical starting frequency for a 36" detonation tube without a nozzle, the engine did not self-actuate. In Fig. 6a, the frequency of the engine, normalized by the critical frequency determined experimentally, is plotted versus time. At approximately 1.7 seconds, the clutch was disengaged and the engine quickly decelerated. The power produced by this configuration is plotted in Fig. 6b. While the hybrid engine was being driven by the electric starter motor, the hybrid engine was producing approximately 8 hp—not enough to self-actuate at that starting frequency. The power produced was calculated by integrating the pressure in the cylinder head timed with the volume displaced by the piston movement.

The maximum power produced by this hybrid engine was approximately 20 hp while still producing 50 lbf of thrust. In Fig. 7a, the frequency of this run normalized by the critical frequency is plotted verses time. Notice that the engine was operating above the critical frequency. The power and thrust produced by this engine are plotted in Fig 7b and c respectively.

Analysis

As evident in the experimental results, there was a starting frequency, above which the hybrid piston-PDE would self-actuate and continue to operate after the electric "starter" motor was disengaged. Below this critical frequency the hybrid engine would quickly stop. The critical frequency for



(a) (b)

(c)

Figure 7. Above the critical starting frequency, the hybrid piston-PDE self actuated: (a) normalized frequency versus time showing self-actuation and acceleration of the hybrid engine, (b) calculated power output of the hybrid engine, and (c) thrust

this hybrid engine was a result of the different time constants for the piston movement and the detonation tube "blow down" event. The time constant for the piston engine is defined as

$$t_p = \frac{2}{f_{crank}} \tag{1}$$

where f_{crank} is the frequency of the crankshaft. The time constant for the "blow down" event is the time required for the pressure in the detonation tube to decrease to 1/3 of the gage pressure behind the detonation wave.

The time constant of the blow-down event can be altered by changing the length of the detonation tube or installation of a nozzle on the end of the detonation tube. The time constant of the piston movement can be altered by changing the operating frequency of the engine.

For all of the conditions tested, the time constant of the detonation-tube-blow-down was smaller than that of the piston movement. If the difference between the magnitude of the time constants was too large, the blow down process would occur while the piston was effectively stationary; therefore little or no

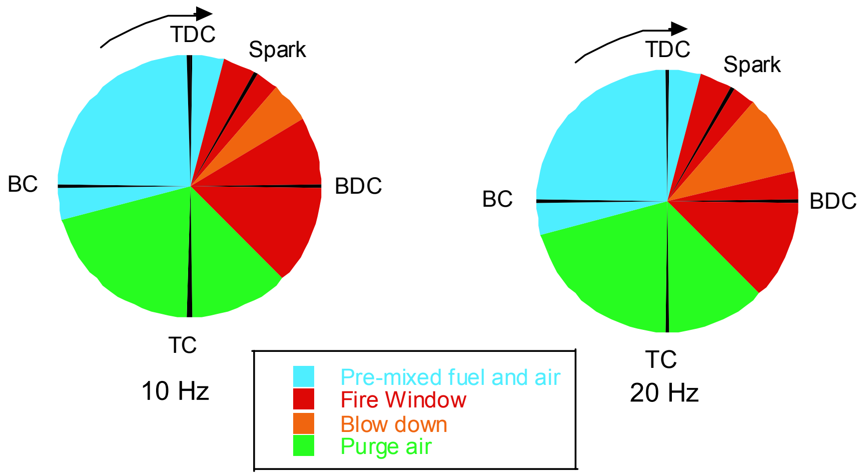


Figure 8 Engine timing and blow-down pressure during a cycle at two different frequencies

PdV work would be extracted from the detonation pressure. By increasing the starting frequency, and lengthening the detonation tube, the time constants of the piston movement and blow down process were similar enough that the power extracted by the piston exceeded the requirement to self-actuate. In Fig. 8, a diagram of the hybrid-engine-timing is given for two different operating frequencies. In these diagrams, the time constant for the piston travel is represented by 90 degrees of the circle from TDC to BDC. The time constant of the blow down process is represented by 18 degrees at 10 Hz and the 36 degree at 20 Hz. From these diagrams, it can be seen that at the higher frequencies, the blow down process occurs over a larger portion of the piston movement.

The critical frequency of the hybrid piston-PDE was calculated for each configuration by estimating the power required for self-actuation and equating that with the PdV work extracted as a function of frequency. The power required for self-actuation included the power required for the system friction and the power required to actuate the valves. Estimates for the power required were taken from Heywood[3]. Figure 9, shows the power required and the power produced plotted as a function of the frequency normalized by the critical frequency. The critical frequency for this particular configuration was calculated to be a detonation frequency of 5 Hz which was within a Hertz of the experimentally determined value. A better method for determining the parasitic system requirements would be to measure this power on a dynamometer.

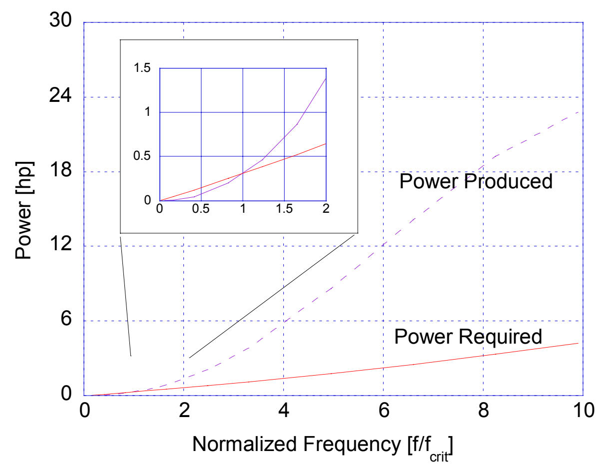
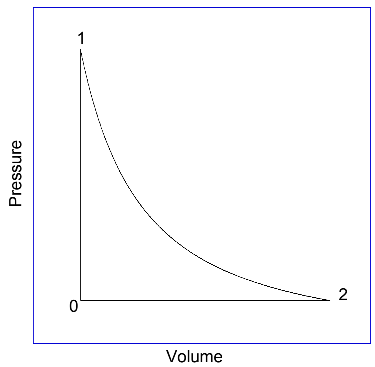


Figure 9. Hybrid piston-PDE critical frequency

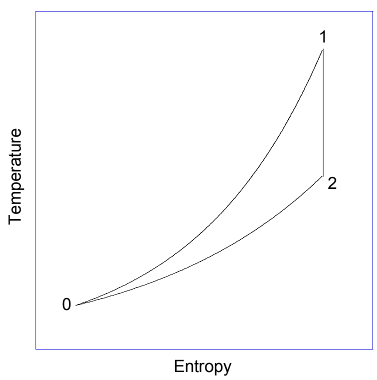
In Fig. 10a the ideal T-s diagram for the hybrid piston-PDE is given and in Fig. 10b the ideal P-v diagram is given. The ideal thermodynamic piston-PDE cycle consists of a constant volume heat addition process (0-1) followed by an isentropic expansion process (1-2). This cycle is very similar to the Air-Standard Otto cycle except there is no isentropic compression of the working fluid before the constant volume heat addition. Of course the method for achieving constant volume combustion is significantly different. This cycle would be impractical for constant pressure combustion. A general discussion of PDE cycle efficiency and the advantage of constant volume versus constant pressure combustion are given by Bussing and Pappas [4]. The ideal steady-cycle-thermal efficiency of the hybrid piston-PDE is given by Eq. (2).

$$\eta = 1 - \gamma \left[\frac{\left(\frac{T_1}{T_0}\right)^{\frac{1}{\gamma}} - 1}{\left(\frac{T_1}{T_0}\right) - 1} \right] \tag{2}$$

Where γ is the ratio of specific heats and T is temperature.



(a)



(b)

Figure 10. Ideal hybrid piston-PDE cycle: a) P-v diagram, b) T-s diagram

The measured thrust of the hybrid piston-PDE was lower compared to the conventional PDE[2]. The volume of the cylinder was approximately 10% of the detonation tube. Removing all of the work from the higher pressure gas prior to blow-down would ideally decrease the pressure in the detonation tube by 14.4%. However, experiments conducted on the hybrid piston-PDE showed that the thrust produced by the hybrid engine was approximately 1/2 that of the thrust on a PDE alone. A pressure trace for the two different engines is plotted in Fig. 11. The pressure of the shock wave traveling down the detonation tube was 2.6 times greater for the PDE alone. The blow-down pressure for the PDE was 20% higher than the blow-down pressure of the hybrid engine. In the hybrid piston-PDE the DDT was occurring as the piston was receding creating an expansion wave and hindering the DDT process. Additionally, there may have been some variability in the performance of the four detonation tubes on the hybrid-piston-PDE. These phenomena contribute to the difference in thrust between the two engines.

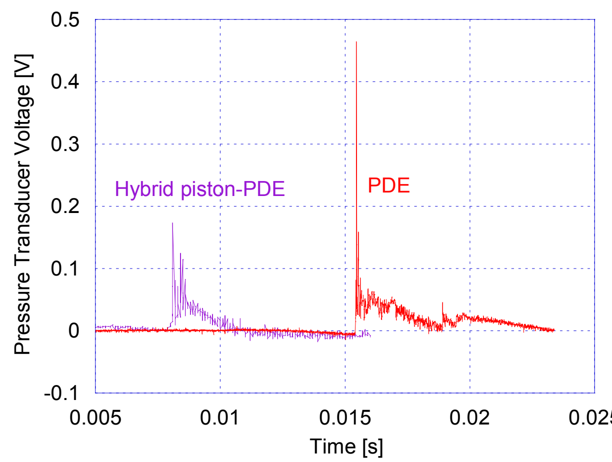


Figure 11. Pressure transducer voltage near the closed end of the detonation tube

No attempt was made to govern the frequency of the hybrid piston-PDE during these experiments. The rotational frequency of the hybrid piston-PDE could be governed in several ways. Reducing the fill fraction of the detonation tube is the most obvious. The equivalence ratio of the charge could also be used to govern the hybrid piston-PDE.

Perhaps one of the best ways to govern the hybrid engine is to alter the spark timing. There is an optimum-spark-timing, for extracting power from the detonation. By moving the spark off this optimum timing, less work is extracted from the detonation, which would control the rotational speed of the engine, and generate more thrust. Finally, the detonation tube itself could be used to govern the rotational speed of the engine. Nozzle geometry and tube length affect the blow-down time, which affects the amount of work that is extracted by the pistons and also the thrust. Actively changing the geometry of the detonation tube while the engine is operating could be used to govern this hybrid engine.

Summary and Conclusions

A hybrid piston-pulse detonation engine was constructed. The device provided a means of extracting shaft power from a pulsed detonation engine while still providing significant thrust. The hybrid engine constructed was not optimized. It was a "proof-of-concept" engine. The performance of the hybrid piston-PDE can be improved by designing the piston engine specifically for this hybrid application. Additional experiments concerning power extraction, self-actuation and self-aspiration are planned.

Acknowledgements

Gratitude is expressed to the technicians who worked on this project: Walt Balster and Dwight Fox (ISSI). Some of the fabrication that was done was shear artwork. Thanks to Charley Smith (ISSI)for his consultations. The authors would also like to thank Jeff Stutrud (AFRL/PRTS) and Jason Parker (ISSI) for their computer programs used to collect and analyze the data, and Mike Bruggeman (AFRL/PROE)for his artistic drawing of the hybrid piston-PDE shown in Fig. 1b. The authors would also like to acknowledge the technical leadership of Dr. Mel Roquemore and Dr. Robert Hancock (AFRL/PRTS).

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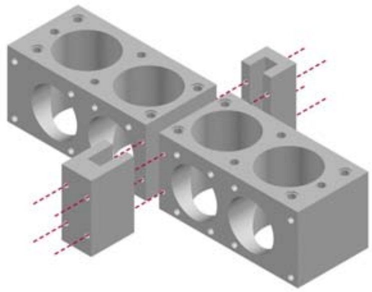
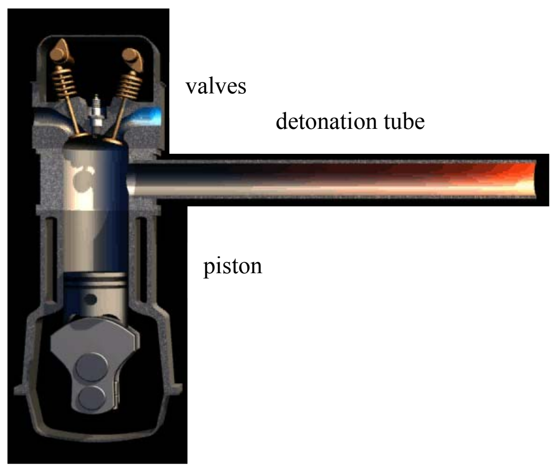


(a)



(b)

Figure 1 Spacer bock: a) 3D cad drawing and b) Drawing of a cross section of the assembled hybrid piston-PDE

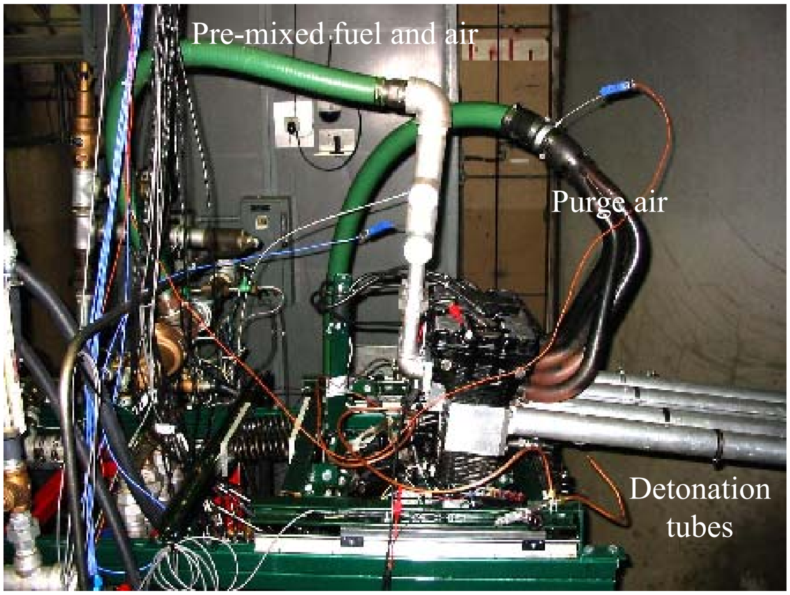


Figure 2 Picture of the hybrid piston PDE

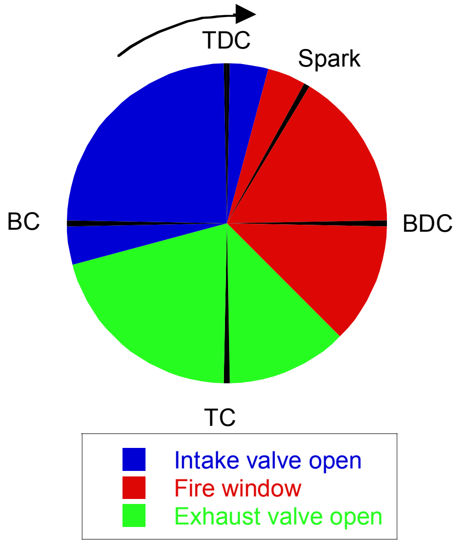


Figure 3 Valve and spark timing relative to piston position, note that the crankshaft makes two revolutions for every one that the camshaft makes. (TDC is top dead center, BDC is bottom dead center, TC is top center and BC is bottom center)

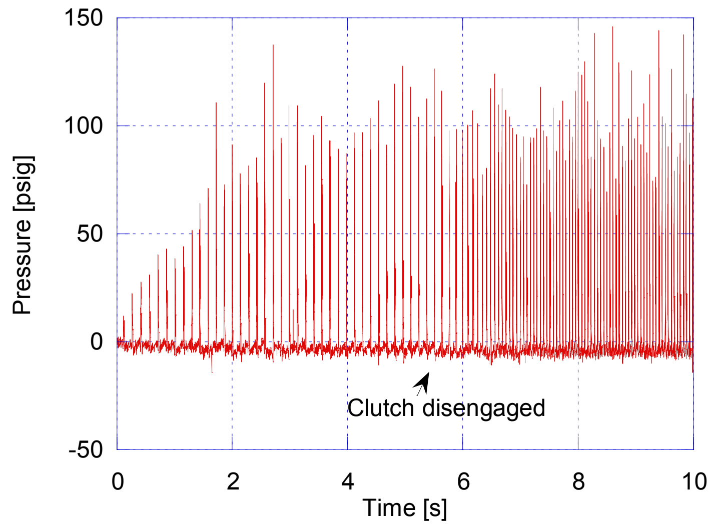


Figure 4 Instantaneous head pressure verses time: accelerating hybrid-piston-PDE

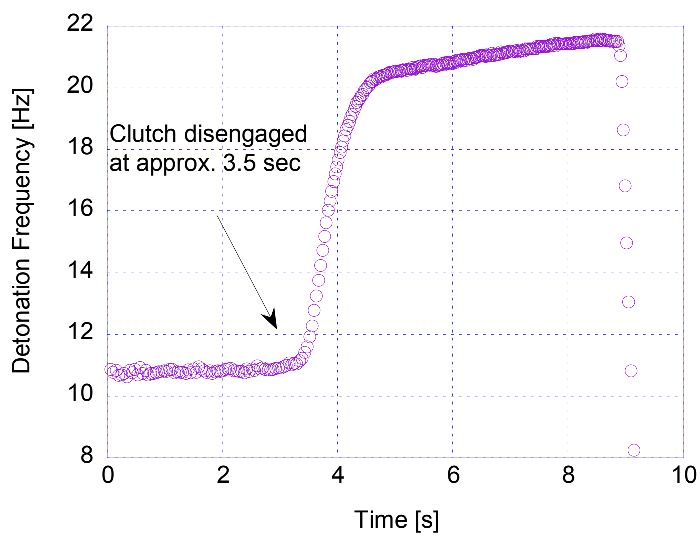
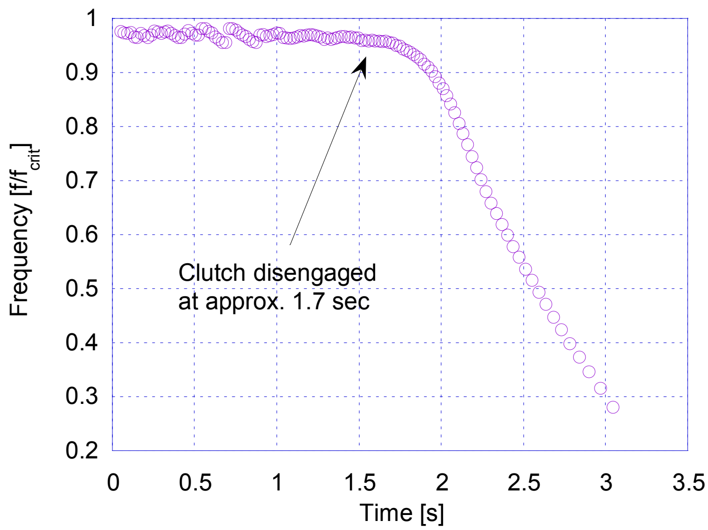


Figure 5 Detonation tube frequency verses time



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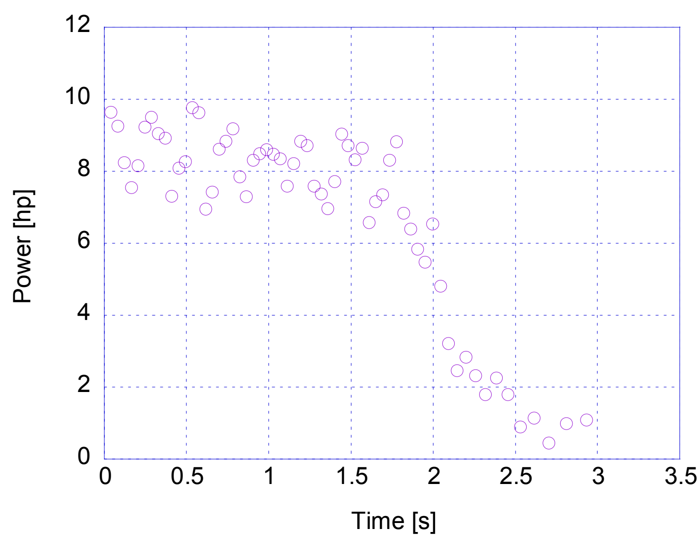
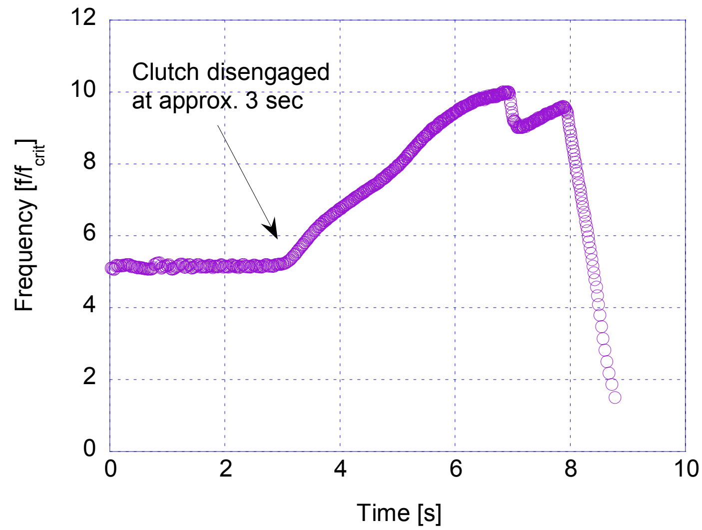


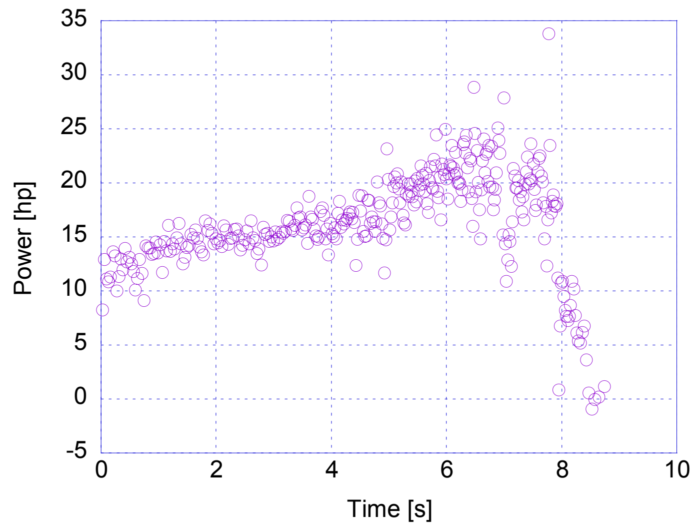
(b)

Figure 6 Below the critical starting frequency the hybrid piston-PDE failed to self-actuate, (a) normalized frequency verses time and (b) calculated power output during this experiment



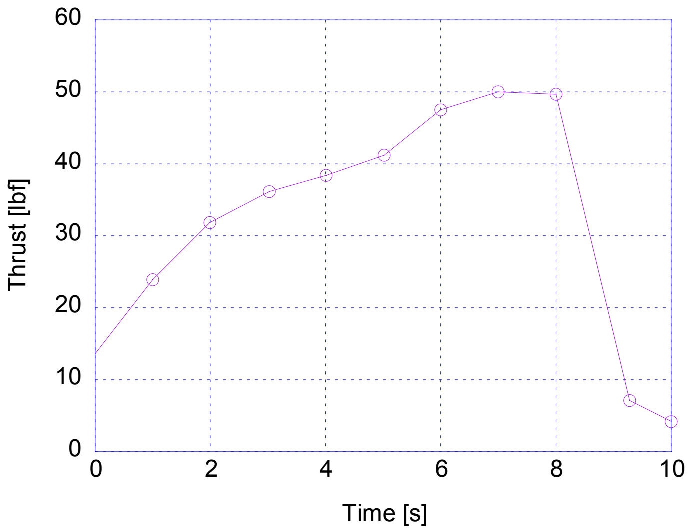
Clutch disengaged
at approx. 3 sec
Frequency [f/f$_{crit}$]
Time [s]

(a)



Power [hp]
Time [s]

(b)



(c)

Figure 7 Above the critical starting frequency, the hybrid piston-PDE self actuated: (a) normalized frequency versus time showing self-actuation and acceleration of the hybrid engine, (b) calculated power output of the hybrid engine, and (c) thrust.

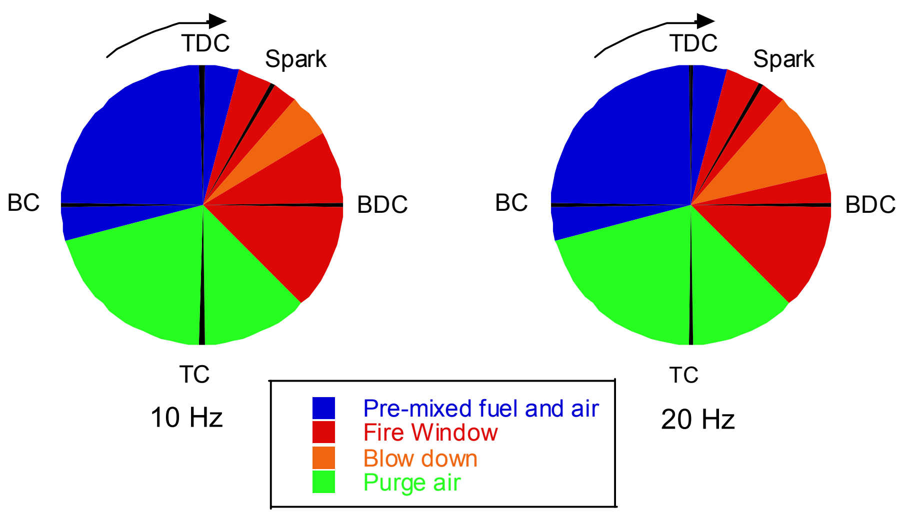


Figure 8 Engine timing and pressure during a cycle at two different frequencies

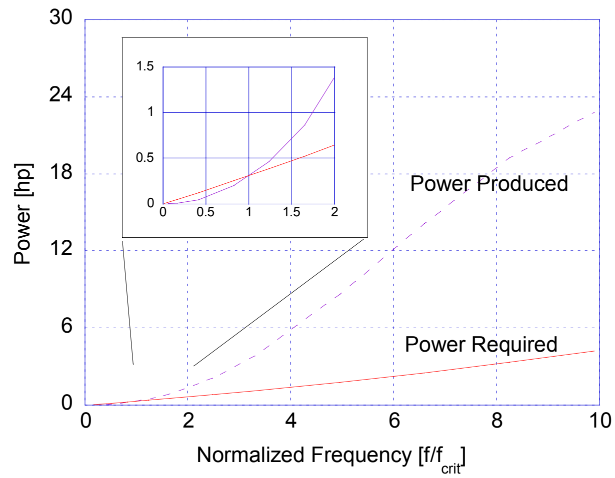
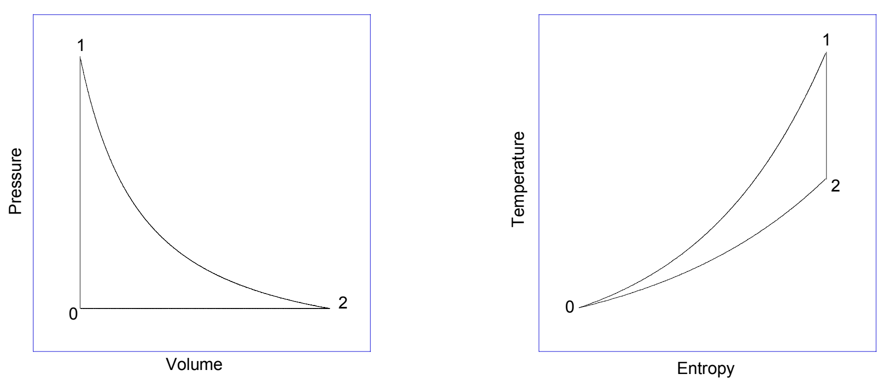


Figure 9 Hybrid piston-PDE critical frequency



(a) (b)

Figure 10 Ideal hybrid piston-PDE cycle: a) P-v diagram, b) T-s diagram

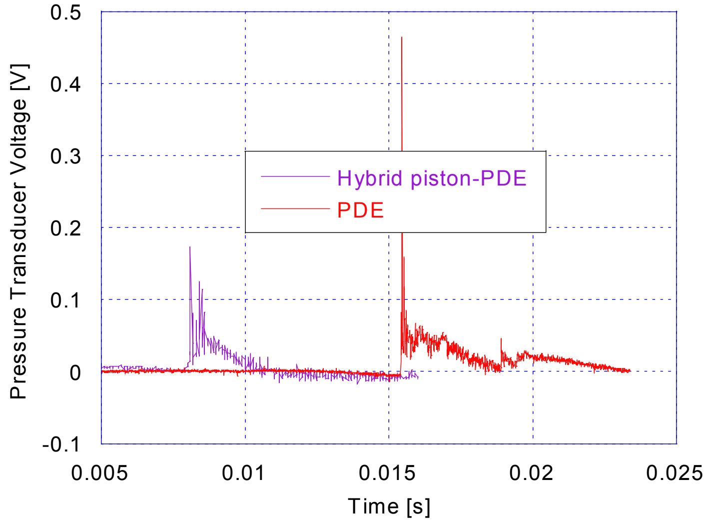


Figure 11 Pressure transducer voltage near the closed end of the detonation tube